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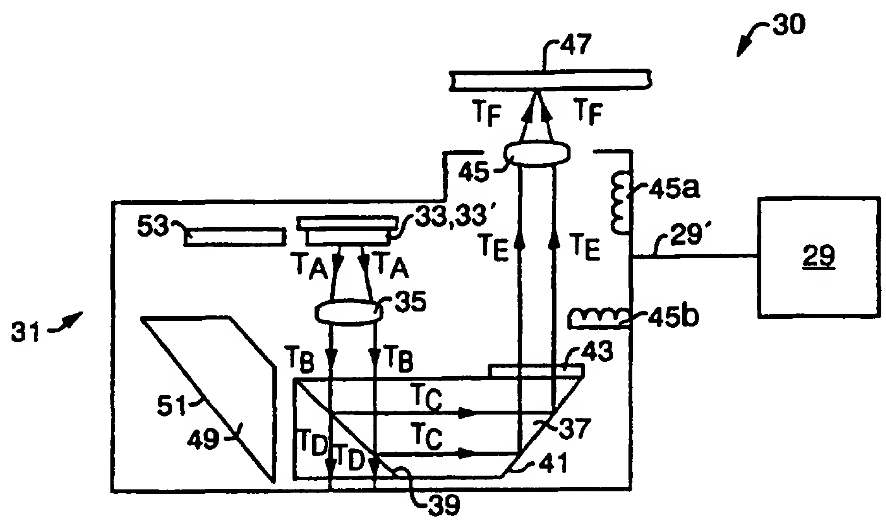

(57) Abstract

A compact defect detection system is provided that comprises an optical pickup and a controller. As a surface of a semiconductor wafer is scanned by the defect detection system, the optical pickup generates a detector current signal that varies with the presence and the absence of defects on the surface of the semiconductor wafer. The controller monitors and interprets the generated detector current signal to affect defect detection. Because the wafer is scanned at a known rate, the size and the location of defects can be determined. Preferably defect-free wafers are scanned through the defect detection system to generate reference signals that may be used for comparison purposes with subsequently scanned production wafers. An array of optical pickups or a deflector may be employed to increase the portion of the semiconductor wafer scanned during defect detection.

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METHOD AND APPARATUS FOR IMPROVED DEFECT DETECTION

BACKGROUND OF THE INVENTION

The present invention relates to defect detection technology, and more specifically to technology for detecting defects on the surface of semiconductor wafers and the various thin films grown or deposited on such wafers.

In the semiconductor device fabrication industry a single defect can destroy an entire wafer die by shorting a junction region or open-circuiting a gate electrode of an essential semiconductor device. Defects also degrade device performance and reliability by creating leakage paths, generating undesirable localized fields, and the like.

A defect can arise when a particle lands on a wafer or when a device pattern is improperly transferred to the wafer (leaving voids or unwanted materials thereon). Particles commonly arise from humans, the atmosphere, the wafer itself, as well as from films deposited or grown on the wafer. Unwanted materials include residual metals, dielectrics, photoresist, photoresist developer, and other similar materials which may erroneously remain on the wafer.

One of the largest hurdles to defect control is identifying defect sources in a timely manner so that a large number of subsequently processed wafers are not contaminated (i.e., so as to eliminate defect propagation). Conventional approaches to defect source identification have been largely unsuccessful and defect propagation related scrap costs as high as three million dollars a day have been reported.

An ideal fabrication system performs defect detection following each processing step and for each wafer processed. In this manner, a processing step can be identified as a defect source immediately after its starts to generate defects and before additional wafers are

contaminated. Unfortunately, with conventional defect detection systems such frequent detection is impractical because each defect detection measurement must be performed in a special measurement chamber (e.g., ex-situ from any automated semiconductor processing tools being employed) containing expensive measurement equipment. The time required to transfer a wafer to the measurement chamber, perform defect detection, and transfer the wafer to the next processing step location can add several hours to the wafer's total fabrication time if defect detection is performed following each processing step. Defect detection following each processing step, therefore, is prohibitively expensive in terms of both throughput and cost per wafer processed. Additionally, because defect detection measurements must be performed ex-situ, additional defects can arise during wafer transfer from the processing tool to the defect detection measurement chamber.

An exemplary apparatus for performing conventional defect detection is shown in FIG. 1A. As represented in FIG. 1A, conventional defect detection schemes require a separate measurement chamber 11 to contain the detection system's moving parts and the unavoidable particle generation associated with moving parts. Within the chamber 11, a laser light source 13 is positioned above a substrate support 15. The substrate support 15 comprises a rotating-translating mechanism 17 for rotating and translating a sample wafer 19 positioned thereon, and a clamp 21 for clamping the sample wafer 19 to the rotating-translating mechanism 17 so as to prevent the sample wafer 19 from wobbling during measurement. The light source 13 emits a light beam 23 which is focused on the sample wafer 19. A collection sphere 25 is positioned between the light source 13 and the sample wafer 19. The collection sphere 25 has a first window 25a through which the light beam 23 enters the collection sphere 25 from the light source 13, a second

window 25b through which the light beam 23 travels to the sample wafer 19, a third window 25c through which a reflected portion 23a (see FIG. 1B) of the light beam 23 exits the collection sphere 25, and a fourth window 25d through which (under certain conditions described below) a scattered portion 23b (see FIG. 1C) of the light beam 23 exits the collection sphere 25 (indicating the presence of a defect on the surface of the sample wafer 19). A photomultiplier 27 is positioned adjacent the fourth window 25d for receiving, detecting and amplifying the scattered portion 23b of the light beam 23.

In operation the light beam 23 emitted from the light source 13 passes through the first window 25a and through the second window 25b to a first point on the surface of the sample wafer 19. As represented in FIG. 1B, in the absence of a defect, the light beam 23 strikes a planar wafer surface where a small portion (represented by the arrow 23c) of the light beam 23 is absorbed by the sample wafer 19 and a majority of the light beam 23 (the reflected portion 23a) is reflected from the surface of the sample wafer 19 back through the second window 25b and through the third window 25c. An insignificant amount of the light beam 23 is scattered by the defect-free planar surface of the sample wafer 19. No light, therefore, is detected by the photomultiplier 27 through the fourth window 25d, indicating that no defect is present on the surface of the sample wafer 19.

As represented in FIG. 1C, in the presence of a defect (typically a non-planar surface) a portion of the light beam 23 (represented by the arrow 23c) is absorbed by the defect, a portion of the light beam 23 reflects (the reflected portion 23a), and the remaining portion of the light beam 23 scatters (the scattered portion 23b).

In theory, as the scattered portion 23b strikes the interior surfaces of the collection sphere 25, the

scattered light 23b bounces therebetween until it is eventually directed through the fourth window 25d into the photo-multiplier 27. Because at any given moment the portion of scattered light that is directed through the fourth window 25d is very small, the photo-multiplier 27 is required to amplify the detected scattered light to a usable level. When a sufficient amount of the scattered light 23b is detected by the photo-multiplier 27, the defect is assumed to be present on the surface of the wafer 19.

During defect detection, the sample wafer 19 is rotated so that defect detection is performed along each angular position of the wafer at the radial distance set by the first point. After detection of the light scattered from the first point on the surface of the sample wafer 19, the rotating-translating mechanism 17 translates the sample wafer 19 such that the light beam 23 strikes a second point (e.g., a second radial distance) along the surface of the sample wafer 19. The light beam 23 is reflected and scattered from the second point, as previously described. This process continues until a sufficiently large number of points on the surface of the sample wafer 19 have been illuminated by the light beam 23. A map of defects across the surface of the sample wafer 19 is thereby obtained.

As the above description suggests, conventional defect detection systems require expensive components (e.g., the sphere 25 and the photo-multiplier 27) and long operating times to scan a surface of a wafer. Additionally, each wafer on which defect detection is to be performed must be removed from its normal process flow, transferred to the measurement chamber, measured, and re-introduced to the process flow. Due to the long operating times required to scan representative points along the surface of a wafer, numerous wafers may be processed and contaminated before a single defect detection scan is complete. Furthermore, the large size and cost of the collection sphere 25 and of the

photo-multiplier 27 make it difficult to employ additional collection spheres and photo-multipliers to reduce measurement times by performing defect detection at multiple locations. As such it is impractical to use conventional defect detection systems for timely defect detection (e.g., after each wafer processing step).

As an example, when a sputtering target nears the end of its useful life the target is more likely to generate defects that contaminate wafers processed using the target. Because conventional defect detection systems are unable to provide timely defect detection, frequent sputtering target replacement is necessary to avoid these end of target life defects. As a substitute for defect detection, statistical data is used to determine the average number of times a sputtering target can cycle before an unacceptable number of defects are generated by the target. Each target then is replaced prior to cycling this average number of times. Unfortunately, in practice, relying on such statistical data results in many targets being discarded long before the end of their useful life. With many sputtering targets presently costing approximately $6,000 a piece, frequent sputtering target replacement is an expensive method of defect control.

Accordingly, a method and apparatus is needed for measuring defects rapidly and inexpensively so that defect detection may be performed following each semiconductor device processing step for each wafer processed. Such a method and apparatus will allow for rapid defect source identification, significantly reducing scrap wafer costs due to defect propagation, and will allow sputtering targets to be more fully expended.

SUMMARY OF THE INVENTION

The present invention overcomes the disadvantages of the prior art by providing an inventive defect detection

system with faster operating times, smaller components and few moving parts (reducing particle generation during defect detection). To achieve these features a scattered light or "dark-field" measurement system having an optical pickup is employed. The optical pickup from a compact disc player, digital versatile disc, or the like may be suitable for use within the dark-field measurement system.

Preferably, within the optical pickup, a laser light source is focused on a plane through which a production object (such as a patterned wafer) travels. A first detector (such as a quadrant photodiode) is positioned to collect light reflected from planar surfaces of the object while a second detector (a monitor photodiode) is positioned to collect light scattered from defects or other topographical features on the wafer's surface. Specifically, a polarizing prism is used to separate or "isolate" reflected light from scattered light and to direct the reflected light (having a first polarization state) to the quadrant photodiode and the scattered light (having a second polarization state) to the monitor photodiode. The detector current generated by the monitor photodiode is used to indicate the presence (large detector current) or absence (small detector current) of a defect or topographical feature on the wafer's surface. The detector current from the quadrant photodiode is used to maintain the focus of the laser beam on the surface of the wafer during defect detection via focus controllers within the optical pickup.

Because the scattered and reflected light beams are polarization isolated by the polarizing prism, the large background of reflected light does not affect the detection of the scattered light by the monitor photodiode. The scattered light is easily detected, which allows for reduced size, cost and complexity of the collection and measurement components, and which allows the system to operate at scan rates significantly higher than the rates at which wafers

are typically transported through semiconductor device fabrication systems. Therefore a wafer can be scanned as it travels at its normal speed through a transfer chamber of a semiconductor device fabrication system. No additional time or movement are required for defect detection/identification.

Preferably one or more defect-free wafers is scanned through the inventive defect detection system and the monitor photodiode's detector current (from the defect-free wafer(s)) is stored to create a reference signal. As used herein defect free means within specification tolerance for the process in question. Thereafter as each production wafer is scanned, the monitor photodiode's detector current (i.e., the scattered detection signal) is compared to the reference signal. Any difference between the scattered detection signal and the reference signal indicates the presence of a defect.

The use of a reference signal prevents a pattern feature (i.e., an elevated or recessed planar region) from being mistaken for a defect, and allows pattern defects (e.g., incorrectly shaped and/or incorrectly positioned pattern material) to be identified by their scattered detection signal, which differs from the reference signal.

Because production wafers are scanned at a known rate, the size and location of a defect can be determined. Moreover, because each surface feature (whether particle, pattern feature or pattern defect) produces a unique pattern of detected scattered light intensities and a corresponding unique monitor photodiode current (i.e., a current signature), defect source identification is enhanced.

In order to inspect a wafer's entire surface area an array of laser light sources and a corresponding array of monitor photodiodes may be employed such that many closely spaced points along the surface of the wafer are illuminated by laser light as the wafer travels past the arrays.

Alternatively, several laser light sources with corresponding monitor photodiodes may be positioned in a spaced relationship so as to inspect spaced intervals along the wafer's surface. Moreover, a solid-state non-linear optical deflector such as an acousto-optic deflector may be employed to scan the light source in a first direction while the wafer translates in a second direction so as to scan the entire wafer.

Preferably the inventive defect detection system is located either along the ceiling of a transfer chamber or outside the transfer chamber adjacent one of the transfer chamber's vacuum seal windows and detects light scattered from a wafer as the wafer is moved through the transfer chamber.

With use of the present invention previously non-value added wafer transport time becomes valuable wafer inspection time. Accordingly, the present inventive defect detection system can inspect every production wafer following every processing step to achieve timely defect detection and rapid defect source identification without reducing wafer throughput.

Moreover, in a sputtering process, the costs associated with premature target replacement are avoided as each sputtering target may remain in use until the layers deposited therefrom begin to exhibit signs that the target is nearing the end of its useful life. An approximately 30 percent decrease in target replacement cost is expected with use of the present invention.

Other objects, features and advantages of the present invention will become more fully apparent from the following detailed description of the preferred embodiments, the appended claims and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A, 1B and 1C are perspective side views of a conventional defect detection apparatus as previously described;

FIG. 2 is a schematic diagram of an inventive defect detection apparatus;

FIG. 3A is a side elevational view of a transmitted light beam reflecting from a defect-free wafer surface;

FIG. 3B is a side elevational view of a transmitted light beam scattering from a topographical feature of a wafer's surface;

FIG. 3C is a schematic diagram of the inventive defect detection apparatus of FIG. 2 as the transmitted light beam reflects and scatters from a wafer surface;

FIG. 4A is a top plan view of a multi-sector detector employed within the inventive defect detection apparatus of FIG. 2;

FIG. 4B is a side elevational view of a transmitted light beam impacting an exemplary defect, useful in explaining focusing of the defect detection apparatus of FIG. 2;

FIG. 5A is a side elevational view of the inventive defect detection apparatus of FIG. 2 shown scanning a non-patterned defective wafer;

FIG. 5B is a timing diagram of reflected detector current versus time for the non-patterned defective wafer of FIG. 5A;

FIG. 5C is a timing diagram of scattered detector current versus time for the non-patterned defective wafer of FIG. 5A;

FIG. 6A is a side elevational view of the inventive defect detection apparatus of FIG. 2 shown scanning a patterned, defect-free wafer;

FIG. 6B is a timing diagram of scattered detector current versus time for the patterned, defect-free wafer of FIG. 6A;

FIG. 7A is a side elevational view of the inventive defect detection apparatus of FIG. 2 shown scanning a defective patterned wafer which, aside from the defects, is identical to the patterned, defect-free wafer of FIG. 6A;

FIG. 7B is a timing diagram identical to the timing diagram of FIG. 6B which serves as a reference signal for the method of defect detection described with reference to FIGS. 7A-7D;

FIG. 7C is a timing diagram of scattered detector current versus time for the defective patterned wafer of FIG. 7A;

FIG. 7D is a timing diagram produced by subtracting the reference signal of FIG. 7B from the scattered detector current of FIG. 7C;

FIG. 8 is a top plan view of a semiconductor processing system employing the defect detection apparatus of FIG. 2; and

FIG. 9 is a block diagram of a deflector-based defect detection apparatus for scanning a surface of a semiconductor wafer during defect detection.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 2 is a schematic diagram of an inventive defect detection apparatus 30 which comprises a controller 29 coupled to an optical pickup 31 via a control bus 29'. As used herein coupled means coupled so as to operate and may comprise direct or indirect coupling. The controller 29 comprises a computer, microcontroller or other conventional controlling mechanism for governing the operation of the optical pickup 31 and for interpreting data sent therefrom to the controller 29 (as described below).

The optical pickup 31 comprises a plurality of optical components for focusing a light beam on the surface of a semiconductor wafer and for collecting light scattered from the wafer by defects. Specifically the optical pickup 31 comprises a laser source 33 for emitting a light beam used in defect detection, a collimator lens 35 for collimating the light beam, a polarizing prism 37 having a first surface 39 and a second surface 41 for polarizing and redirecting the collimated light beam, and a quarter wave plate 43 for rotating the polarization of the redirected light beam. The optical pickup 31 further comprises an objective lens 45 having a first focus controller 45a and a second focus controller 45b for focusing and maintaining the focus of the polarization rotated light beam on the surface of a semiconductor wafer 47, a critical angle prism 49 having a first surface 51 for collecting the portion of the light beam reflected by the wafer 47 and for redirecting the reflected light beam, and a quadrant photodiode 53 for collecting the redirected, reflected light beam and for providing reflected light beam position information to the first and the second focus controllers 45a, 45b. Additionally, the optical pickup 31 comprises a monitor photodiode 33′ adjacent the laser source 33 for collecting light scattered by the wafer 47 as described below.

In operation, the laser diode 33 emits a diverging, non-polarized light beam (T_A) toward the collimator lens 35. The collimator lens 35 converts the light beam T_A into a collimated, non-polarized light beam (T_B). The light beam T_B enters the polarizing prism 37 and strikes the first surface 39 of the polarizing prism 37. The first surface 39 is configured to reflect only linearly polarized light of a first polarization state (e.g., horizontally polarized light) toward the second surface 41 of the polarizing prism 37, and to transmit all light in any other polarization state (e.g., light which is vertically

polarized or otherwise polarized). Thus, a portion of the light beam T_B is converted to a collimated, first polarization state light beam (T_C) that travels toward the second surface 41, and the remainder of the light beam T_B travels through the first surface 39 and is not used (light beam T_D).

The second surface 41 reflects the linearly polarized light beam T_C toward the quarter wave plate 43. The quarter wave plate 43 rotates the polarization of the light beam T_C by 45°, converting the linearly polarized light beam T_C to a collimated, circularly polarized light beam (T_E). The light beam T_E then travels to an objective lens 45 which focuses the light beam T_E (forming a focused, circularly polarized light beam (T_F)) on the surface of the wafer 47. The various characteristics of each light beam T_A-T_F are summarized below in Table 1.

TABLE 1

TRANSMITTED BEAM	DESCRIPTION
T_A	diverging and non-polarized
T_B	collimated and non-polarized
T_C	collimated and linearly polarized (first polarization state)
T_D	collimated and all polarizations (except first polarization state)
T_E	collimated and circularly polarized (rotated 45° from first polarization state)
T_F	focused (converging) and circularly polarized

If the light beam T_F strikes a portion of the wafer 47 that is free from topographical features (e.g., free from pattern features or defects), substantially all of the light beam T_F reflects back toward the objective lens 45 along the same direction traveled by and with the same polarization as

the transmitted light beam T_F (FIG. 3A). However, if a portion of the light beam T_F strikes a topographical feature, that portion of the light beam T_F scatters (e.g., is absorbed by the topographical feature and is re-radiated in random directions and with random polarizations) (FIG. 3B). If the topographical feature is significantly smaller than the focal width of the light beam T_F, the majority of the light beam T_F reflects along the same path traveled by the transmitted light beam T_F (forming a reflected and diverging circularly polarized light beam (R_A) as shown in FIG. 3C) and only a small amount of the light beam T_F scatters from the topographical feature in random directions and with random polarizations. Nonetheless, a portion of the scattered light will be directed toward and collected by the objective lens 45 (the scattered and diverging non-polarized light beam (S_A)).

FIG. 3C shows the paths traveled by the light beams R_A and S_A as they travel through the optical pickup 31. The objective lens 45 converts the light beam R_A into a collimated, circularly polarized light beam (R_B), and the light beam S_A into a collimated, non-polarized light beam (S_B). The light beams R_B, S_B then travel to the quarter wave plate 43 where the polarization of each light beam is rotated by 45°. Rotating the polarization of the light beam R_B by 45° converts the light beam R_B from a collimated, circularly polarized light beam to a collimated linearly polarized light beam (R_C) of a second polarization state that is 90° rotated from the first polarization state (e.g., rotating the polarization of a horizontally polarized light beam by 90° converts it to a vertically polarized light beam and vice versa). Rotating the light beam S_B by 45° merely rotates by 45° the individual polarization states of the various randomly polarized light beams comprising the light beam S_B so as to form a collimated and non-polarized light

beam (S_C). The light beams R_C and S_C reflect off the second surface 41 of the polarizing prism 37 and are directed toward the first surface 39.

At the first surface 39, all light in the second polarization state (e.g., all of light beam R_C) and all light in any polarization state other than the first polarization state (e.g., the majority of the scattered light beam S_C) is transmitted through the first surface 39, forming collimated, linearly polarized, second polarization state light beam R_D and collimated, non-polarized light beam S_D. The light beams R_D and S_D travel to the critical angle prism 49 and reflect off the first surface 51 of the critical angle prism 49 toward the quadrant photodiode 53. The quadrant photodiode 53 uses the light beam R_D for maintaining the focus of the objective lens 45 on the surface of the wafer 47 as described below with reference to FIGS. 4A and 4B.

All light in the first polarization state that strikes the first surface 39 of the polarizing prism 37 (e.g., the portion of the light beam S_C that is not transmitted through the first surface 39) reflects off the first surface 39 to form a collimated, linearly polarized, first polarization state light beam (S_E) that travels toward the collimator lens 35. The collimator lens 35 focuses the light beam S_E on the surface of the monitor photodiode 33′ adjacent the laser diode 33, forming a focused (converging) first polarization state light beam (S_F). The various characteristics of each light beam R_A-R_D and S_A-S_F are summarized below in Tables 2 and 3.

TABLE 2

REFLECTED BEAM	DESCRIPTION
R_A	diverging and circularly polarized
R_B	collimated and circularly polarized
R_C	collimated, linearly polarized and rotated 90° from first polarization state (second polarization state)
R_D	collimated and linearly polarized in second polarization state

TABLE 3

SCATTERED BEAM	DESCRIPTION
S_A	diverging and non-polarized
S_B	collimated and non-polarized
S_C	collimated, non-polarized and rotated 45°
S_D	collimated and all polarizations (except first polarization state)
S_E	collimated, linearly polarized in first polarization state
S_F	focused (converging), linearly polarized in first polarization state

To perform defect detection using the defect detection apparatus 30 of FIG. 2, the light detected by the monitor photodiode 33' is monitored (as described more fully below). Light is only detected by the monitor photodiode 33' when the transmitted light beam T_F strikes a topographical feature (e.g., a defect) that scatters a portion of the light beam T_F toward the objective lens 45. Furthermore, only scattered light with a polarization state that lags the first polarization state by 45° reaches the monitor photodiode 33'. Because the reflected light beam R_C is in the second polarization state, none of the strongly

reflected light beam R_A is detected by the monitor photodiode 33'. As such, the defect detection apparatus 30 operates as a dark field microscope as light is only detected by the monitor photodiode 33' when a topographical feature is present and scatters the light beam T_F.

When scattered light strikes the monitor photodiode 33', a scattered detector current signal having a magnitude proportional to the amount of light detected is produced by the monitor photodiode 33'. As described below with reference to FIGS. 5A-7D, this current signal can be used by the controller 29 for defect detection and defect identification.

FIG. 4A is a top view of an exemplary quadrant photodiode 53 having detection sectors 53a-d. While a quadrant photodiode 53 is presently preferred, any suitable multi-sector detector may be employed for the photodiode 53.

Within the quadrant photodiode 53, only the sectors 53a-d which light strikes generate a detection signal (e.g., a detection current). Accordingly, the position of the reflected light beam R_D on the quadrant photodiode 53 can be determined by noting which sectors 53a-d generate a detection current, and by noting the magnitude of the detection current generated by each sector. For instance, as shown in FIG. 4A, when the reflected light beam R_D strikes the photodiode 53 off center, each sector 53a-d detects a different magnitude of light. Based on the detection current differences between the sectors, beam position information is calculated. In FIG. 4A, the reflected light beam R_D is known to be skewed toward the sector 53a because more detection current is generated by the sector 53a than any other sector (sectors 53b-d). This "position information" may be used for focus control.

To focus the transmitted light beam T_F on the wafer 47, the quadrant photodiode 53 provides the above described position information to the first and second focus

controllers 45a, 45b. The focus controllers 45a, 45b use this position information to compute a proper lens position (e.g., proper pitch and yaw) so as to maintain the desired focus of the transmitted light beam T_F. To ensure rapid focus control, the focus controllers 45a, 45b preferably employs digital signal processing circuitry (not shown) for computations, and control lens pitch and yaw via active and passive magnetic coupling. Rapid focus control maintains the focus of the transmitted light beam T_F on the wafer 47 despite small variations in wafer position relative to the optical pickup 31. For example, small variations in wafer position may result due to wafer wobble or vibration during wafer transport (as described below), or due to the wafer bow present in most silicon wafers (e.g., approximately 0.2 mm for 200mm or larger wafers). The importance of maintaining the focus of the transmitted light beam T_F on the wafer 47 is described with reference to FIG. 4B.

FIG. 4B shows a close-up view of the transmitted light beam T_F incident on an exemplary defect 55 on the surface of the wafer 47. By maintaining the narrowest portion of the transmitted light beam T_F (i.e., the focal point) on the wafer 47 a greater percentage of the transmitted light beam T_F impacts the defect 55 and scatters as previously described. Accordingly, by maintaining the transmitted light beam T_F's narrowest portion on the wafer, a defect will scatter a larger percentage of the transmitted light beam T_F, increasing the amount of light detected by the monitor photodiode 33'. That is, with reference to FIG. 4B, the ratio of the defect area $\pi(d/2)^2$ (where d is the diameter of the defect) to the transmitted light beam area $\pi(W/2)^2$ (where W is the width of the light beam) is maximized so that a greater percentage of the transmitted light beam T_F is scattered by the defect 55.

Because the optical pickup 31 rapidly maintains the focus of the transmitted light beam T_F on the wafer 47

despite wafer vibration or wafer movement during defect detection, the defect detection apparatus 30 of FIG. 2 is able to detect very small defects (e.g., 0.1 micrometer defects are detectable when a 780 nanometer laser source is employed as the light source 33).

Optical pickups which can be employed as the optical pickup 31 are well known in the art. For instance, the optical pickup from a compact disc player (such as Olympus Optical Co., Ltd. Model TAOHS-L), a compact disc read-only-memory drive, or from a digital versatile disc player may function as the optical pickup 31. The optical pickup of a compact disc player, for example, maintains focus while a compact disc is scanned at a rate of 1.4 m/sec, a scan rate much higher than that required for wafer defect detection scanning. Furthermore, many optical pickups possess dynamic focal ranges in excess of 1 mm, far greater than the 0.2 mm dynamic focal range required to compensate for wafer bow during defect detection scanning.

The operation of the defect detection apparatus 30 of FIG. 2 is described with reference to FIGS. 5A-5C and FIG. 2. FIG. 5A shows the optical pickup 31 during defect detection scanning of a wafer 47. The wafer 47 contains a first defect 57, a second defect 59, and a third defect 61. The wafer 47 is otherwise free from topographical features. The sizes of the defects 57, 59 and 61 are intentionally exaggerated for clarity.

To perform defect detection scanning, the optical pickup 31 is held stationary while the wafer 47 is translated (e.g., linearly) past the optical pickup 31. Wafer translation may be performed via a motorized wafer support, or preferably, via an end effector during transport of the wafer 47 between two processing chambers (as described below with reference to FIG. 8). It is understood that the wafer 47 alternatively may be held stationary while the optical pickup 31 is translated past the wafer 47.

In operation, a wafer 47 travels along a predetermined path at a predetermined speed. The light source 33 emits the transmitted light beam T_F which strikes the top surface of the wafer 47 as the wafer 47 travels beneath the optical pickup 31. The transmitted light beam T_F reflects and scatters off the top surface of the wafer 47 forming a reflected light beam R_A and a scattered light beam S_A as described previously with reference to FIGS. 2-3C.

The reflected light beam R_A travels to the quadrant photodiode 53 (arriving at the quadrant photodiode 53 as reflected light beam R_D). In response to the reflected light beam R_D, quadrant photodiode 53 generates a "reflected" detector current I_R indicative of the intensity of the reflected light beam R_D. The reflected detector current I_R is a composite of the individual sector 53a-d detector currents which are sent to the focus controllers 45a, 45b for maintaining the focus of the transmitted light beam T_F on the wafer 47 (as previously described).

Likewise, a portion of the scattered light beam S_A (e.g., the scattered light beam S_F) travels to the monitor photodiode 33' and generates a "scattered" detector current I_S indicative of the intensity of the scattered light beam S_F. The controller 29 interprets the scattered detector current information and detects the defects 57, 59 and 61 as described below with reference to FIGS. 5B and 5C.

FIGS. 5B and 5C are graphs of reflected and scattered detector currents versus time, respectively, as the wafer 47 of FIG. 5A is scanned by the transmitted light beam T_F. With reference to FIGS. 5B and 5C, at time t_0, the transmitted light beam T_F strikes the leftmost edge of the wafer 47 at a location d_0, generating the reflected light beam R_A and the scattered light beam S_A. Because the wafer 47 is free from defects or other topographical features at the location d_0, the transmitted light beam T_F undergoes

little scattering so that the scattered light beam S_A is negligibly small.

The reflected light beam R_A travels to and is detected by the quadrant photodiode 53 as reflected light beam R_D. The quadrant photodiode 53 measures the intensity of the reflected light beam R_D and generates a corresponding "defect-free" reflected detector current level I_{R0} (FIG. 5B). The quadrant photodiode 53 provides the detector current level I_{R0} to the focus controllers 45a, 45b in the form of a current level from each sector 53a-d. Because the scattered light beam S_A is negligibly small, the monitor photodiode 33' generates a small "defect-free" scattered detector current level I_{S0} (FIG. 5C).

As the wafer 47 continues to translate to the left, between times t_0 and t_1 the transmitted light beam T_F scans the surface of the wafer 47 between locations d_0 and d_1. Because the surface of the wafer 47 is free from defects or other topographical features between d_0 and d_1, the defect-free reflected and scattered detector current levels I_{R0}, I_{S0} are maintained by the quadrant photodiode 53 and the monitor photodiode 33', respectively, during this time period (as indicated in FIGS. 5B and 5C).

At location d_1 (FIG. 5A), which corresponds to time t_1 (FIGS. 5B and 5C), a portion of the transmitted light beam T_F strikes the first defect 57. Due to scattering effects (described previously with reference to FIG. 3B), the first defect 57 decreases the intensity of the reflected light beam R_D detected by the quadrant photodiode 53 and increases the intensity of the scattered light beam S_F detected by the monitor photodiode 33'.

Between times t_1 and t_2, the wafer 47 translates so that the transmitted light beam T_F scans the first defect 57 located between locations d_1 and d_2. During this time period (t_1-t_2) a large portion of the transmitted light beam T_F strikes the first defect 57. Due to scattering, the

reflected light beam R_D detected by the quadrant photodiode 53 reduces and the reflected detector current decreases (e.g., the reflected detector current drops to the "defect present" reflected detector current level I_{R1}). The scattered light beam S_F detected by the monitor photodiode 33' increases and the scattered detector current increases (e.g., the scattered detector current increases to the "defect present" scattered detector current level I_{S1}). These changes in detector currents are communicated to the controller 29 and to the focus controllers 45a, 45b. The controller 29 detects the presence of the first defect 57 by monitoring the increased scattered detector current produced by the monitor photodiode 33'.

As the wafer 47 continues to translate, at time t_2, the transmitted light beam T_F no longer strikes the first defect 57 and the amount of reflected light rises while the amount of scattered light decreases. During the time period from t_2 to t_3 the transmitted light beam T_F scans the region d_2 to d_3 of the wafer 47 which is free from defects or other topographical features. Accordingly, little scattering results and the defect-free reflected detector current level I_{R0} and scattered detector current level I_{S0} are produced and maintained by the quadrant photodiode 53 and the monitor photodiode 33', respectively.

Similar results are obtained during the remaining defect detection scan of the wafer 47. As the wafer 47 continues to translate, between time t_3 to t_4, the second defect 59 (d_3-d_4) is scanned and due to scattering the "defect present" reflected detector current level I_{R1} and scattered detector current level I_{S1} are produced by the quadrant photodiode 53 and the monitor photodiode 33', respectively.

Between times t_4 and t_5, the transmitted light beam T_F strikes the defect-free surface of the wafer 47 between locations d_4 and d_5. Thus the transmitted light beam T_F

undergoes little scattering and the quadrant photodiode 53 outputs the defect-free reflected detector current level I_{R0} while the monitor photodiode 33′ outputs the defect-free scattered detector current level I_{S0}.

Between times t_5 and t_6, a reduced reflected light beam intensity R_D is detected by the quadrant photodiode 53 due to scattering from the third defect 61 as the transmitted light beam T_F scans between the locations d_5 and d_6 of the wafer 47. The monitor photodiode 33′, therefore, detects a larger scattered light beam intensity S_F. Thus, the defect present reflected detector current level I_{R1} and scattered detector current level I_{S1} are produced between t_5 and t_6.

Between times t_6 and t_7, the transmitted light beam T_F strikes the defect-free surface between locations d_6 and d_7 of the wafer 47. The transmitted light beam T_F undergoes little scattering and the quadrant photodiode 53 outputs the defect-free reflected detector current level I_{R0}. The monitor photodiode 33′ outputs the defect-free scattered detector current level I_{S0}.

After time t_7, the wafer 47 translates such that the transmitted light beam T_F no longer strikes the surface of the wafer 47. No light is reflected or scattered to either the quadrant photodiode 53 or the monitor photodiode 33′, and each detector current level rapidly drops to zero and remains at zero, signifying the rightmost edge of the wafer 47 (location d_7) and the end of the wafer 47′s defect detection scan.

All of the detector current information described above is communicated to the controller 29 and/or the focus controllers 45a, 45b. The controller 29 monitors the scattered detector current produced during the wafer scan, and identifies defects when the scattered detector current increases above a predetermined level (e.g., the defect-free scattered detector current level I_{S0}). Because the wafer 47

travels at a known rate, the increase in scattered detector current during time periods t_1 to t_2, t_3 to t_4, and t_5 to t_6 enables the controller 29 to identify the specific location of each defect, the first defect 57 between locations d_1 and d_2, the second defect 59 between locations d_3 and d_4, and the third defect 61 between locations d_5 and d_6, respectively.

The focus controllers 45a, 45b monitor the position of the reflected light beam R_D on the quadrant photodiode 53 during the wafer scan and adjust the position of the lens 45 so as to maintain the focus (e.g., the focal point) of the transmitted light beam T_F on the wafer 47. Because of the rapid operation of the focus controllers 45a, 45b, the wafer scan can be performed very quickly while still allowing small defects to be detected.

FIGS. 5A-5C are also useful in describing a preferred method of detecting defects on a patterned wafer. When defect detection is performed on a patterned wafer the topographical features of the pattern on the wafer can (due to scattering) produce an increase in the scattered light beam S_F intensity detected by the monitor photodiode 33'. Accordingly, when the inventive defect detection apparatus 30 of FIG. 2 scans a patterned wafer, the controller 29 must be preprogrammed to distinguished defects (particle defects and pattern defects) from non-defective pattern features.

Because patterned features are typically planar (unlike the non-uniform surface of particle defects), the scattered detector current generated during a pattern feature scan (i.e., the current signature of the pattern feature) differs from the scattered detector current generated during a particle defect scan. Thus, a properly programmed controller 29 can distinguish particle defects from pattern features.

A preferred method of detecting defects on a patterned wafer is to scan a defect-free reference wafer to obtain a reference scattered detector current signal for

comparing to subsequent wafer scans. Comparison with a defect-free reference signal not only identifies particle defects, but also allows pattern defects to be distinguished from non-defective pattern features, as described below.

FIG. 6A shows a defect-free patterned wafer 65a having a patterned film 67 deposited thereon. The patterned film 67 contains pattern features 67a-67h. The optical pickup 31 is shown emitting the transmitted light beam T_F and detecting the reflected light beam R_A and scattered light beam S_A as previously described with reference to FIGS. 5A-C. The patterned film 67 and the surface of the patterned wafer 65a are free of defects of any kind. Thus, a scan of the wafer 65a produces a defect-free reference signal to which other wafer scans can be compared.

FIG. 6B shows a graph of scattered detector current versus time for the monitor photodiode 33′ as the patterned, defect-free wafer 65a of FIG. 6A is scanned by the transmitted light beam T_F. It is understood that the detector current signature of a patterned feature may vary greatly depending on the relative size of the patterned feature and the wavelength of the transmitted light beam T_F. The graph of FIG. 6B is merely exemplary.

The graph of the reflected detector current versus time for the quadrant photodiode 53 is similar to previously described FIG. 5B and will not be described herein. It is understood that the focus controllers 45a, 45b continuously monitor the quadrant photodiode 53 to ensure that the transmitted light beam T_F remains focused on the wafer 65a during the wafer scan.

At time t_0, the transmitted light beam T_F strikes the leftmost edge of the defect-free patterned wafer 65a at a location d_0 and generates the scattered light beam S_A. Because the patterned wafer 65a is free from defects or other topographical features at the location d_0, the amount of scattered light produced is small. Nonetheless, any

scattered light, assuming it has the proper polarization, travels to and is detected by the monitor photodiode 33′ as scattered light beam S_F. The monitor photodiode 33′ measures the intensity of the scattered light beam S_F and generates a "defect/feature free" detector current level I_{S0}.

Between times t_0 and t_1, the patterned wafer 65a translates to the left and the transmitted light beam T_F scans the surface of the wafer 65a between locations d_0 and d_1. Because the surface of the patterned wafer 65a is free from defects or other topographical features between locations d_0 and d_1, the defect/feature free detector current level I_{S0} is generated by the monitor photodiode 33′ between times t_0 and t_1.

At location d_1 (at time t_1) a portion of the transmitted light beam T_F strikes the first pattern feature 67a. Like the defects 57-61 of FIG. 5A, the first patterned feature 67a causes scattering and increases the intensity of the scattered light beam S_F detected by the monitor photodiode 33′. Accordingly, an increased scattered detector current I_{S2} indicative of a pattern feature (i.e., a "feature present" detector current level I_{S2}) is observed during the time period t_1 to t_2 as the transmitted light beam T_F scans the first pattern feature 67a. In practice, although the feature present detector current level I_{S2} is useful for identifying a pattern feature, the shape or the overall current signature of the pattern feature is more identifiable. Knowledge of a pattern feature's specific current signature enables defective pattern feature identification.

As the patterned wafer 65a continues to translate, at time t_2, the transmitted light beam T_F no longer strikes the pattern feature 67a, and little scattering results. Because the patterned wafer 65a is free from defects or pattern features within the region d_2 to d_3, the

defect/feature free detector current level I_{S0} is produced during the time period t_2 to t_3.

Similar results are obtained during the remainder of the defect detection scan of the patterned, defect-free wafer 65a. Between times t_3 and t_4, t_5 and t_6, t_7 and t_8, t_9 and t_{10}, t_{11} and t_{12}, t_{13} and t_{14}, and t_{15} and t_{16}, the feature present detector current level I_{S2} is produced by the monitor photodiode 33′ due to scattering from the pattern features 67b, 67c, 67d, 67e, 67f, 67g, and 67h, respectively. Between times t_4 and t_5, t_6 and t_7, t_8 and t_9, t_{10} and t_{11}, t_{12} and t_{13}, t_{14} and t_{15}, and t_{16} and t_{17}, the transmitted light beam T_F does not strike any pattern features. During these time periods the transmitted light beam T_F undergoes little scattering and the monitor photodiode 33′ outputs the defect/feature free detector current level I_{S0}. After time t_{17}, the scattered detector current rapidly drops to zero and remains at zero, signifying the rightmost edge of the wafer (location d_{17}) and the end of the defect detection scan for the patterned, defect-free wafer 65a.

As the detector current information described above is generated (i.e., in real time) it is communicated to the controller 29. Because the wafer 65a travels at a known rate, the increase in scattered detector current during time periods t_1 to t_2, t_3 to t_4, t_5 to t_6 etc., enables the controller 29 to identify the specific location of each pattern feature (e.g., the first pattern feature 67a between locations d_1 and d_2, the second pattern feature 67b between locations d_3 and d_4, the third pattern feature 67c between locations d_5 and d_6, etc.).

The focus controllers 45a, 45b monitor the position of the reflected light beam R_D on the quadrant photodiode 53 in real time during the wafer scan and adjust the position of the lens 45 so as to maintain the focal point of the transmitted light beam T_F on the defect-free patterned wafer 65a. Because the patterned wafer 65a is

defect free, the scattered detection current signal shown in FIG. 6B may be stored by the controller 29 as a defect-free reference signal and compared to the scattered detection signal produced during subsequent wafer scans, as described below with reference to FIGS. 7A-7D.

FIG. 7A shows a defective patterned wafer 65b having a first patterned wafer defect 73 and a second patterned wafer defect 75. Except for the defects 73 and 75, the defective patterned wafer 65b of FIG. 7A is identical to the defect-free patterned wafer 65a of FIG. 6A. That is, the defective patterned wafer 65b contains the patterned film 67 of FIG. 6A. As in FIG. 6A, the optical pickup 31 of FIG. 7A is shown emitting the transmitted light beam T_F and detecting the reflected light beam R_A and the scattered light beam S_A.

FIG. 7B shows the graph of scattered detector current versus time as the defect-free patterned wafer 65a of FIG. 6A is scanned by the transmitted light beam T_F (as described with reference to FIGS. 6A and 6B). FIG. 7B is therefore identical to FIG. 6B and serves as a "reference signal" to which the scattered detector signal of the defective patterned wafer 65b of FIG. 7A is compared.

FIG. 7C shows a graph of scattered detector current versus time as the defective patterned wafer 65b of FIG. 7A is scanned by the transmitted light beam T_F. Only the differences between the reference signal of FIG. 7B and the scattered detector current signal of FIG. 7C will be described. These differences occur between times t_A to t_C and t_D to t_F.

Referring to FIGS. 7A and 7C, between times t_A and t_B a portion of the transmitted light beam T_F strikes the first patterned wafer defect 73 located between wafer location d_A and d_C and (as with the defects 57-61 of FIG. 5A) the intensity of the scattered light beam S_F detected by the monitor photodiode 33′ increases due to scattering from the

defect 73. Thus the first patterned wafer defect 73 causes the scattered detector current produced between times t_A and t_B to be higher in FIG. 7C than in FIG. 7B (where no defect is present).

Thereafter at time t_B (where the first patterned wafer defect 73 overlaps the pattern feature 67c), the more irregular topography of the first patterned wafer defect 73 (compared to the topography of the pattern feature 67c) causes additional scattering by the defect 73. Thus at t_B, the scattered detector current level for the wafer 65b increases above the scattered detector current level I_{S2} (which occurs at time t_B in the reference signal). The scattered detector current level for the wafer 65b remains above I_{S2} until t_C when the transmitted light beam T_F passes the first patterned wafer defect 73 and the monitor photodiode 33′ generates the scattered detector current level I_{S2}.

A similar difference between the graphs of FIG. 7B (defect-free patterned wafer 65a) and FIG. 7C (defective patterned wafer 65b) occurs between times t_D and t_F. With reference to FIG. 7B, the graph of the defect-free patterned wafer 65a, between time t_D and t_E the transmitted light beam T_F strikes the pattern feature 67e and produces the scattered detector current level I_{S2}. For the defective wafer 65b, however, the transmitted light beam T_F strikes a portion of the second patterned wafer defect 75 which overlaps the pattern feature 67e. The more irregular topographical features of the second patterned wafer defect 75 cause additional scattering. An increase in the scattered light beam intensity S_A results so that between times t_D and t_E the scattered detector current level of the monitor photodiode 33′ rises above scattered detector current level I_{S2} (FIG. 7C). Thereafter at time t_E (where the second patterned wafer defect 75 no longer overlaps the pattern feature 67e) the second patterned wafer defect 75 maintains the scattered

detector current above the scattered detector current level I_{S2}.

The detector current remains at an increased level over the reference signal of FIG. 7B between times t_E and t_F until the transmitted light beam T_F no longer strikes the second patterned wafer defect 75. The monitor photodiode 33' provides the above described detector current information to the controller 29.

To detect and identify the locations of the first patterned wafer defect 73 and the second patterned wafer defect 75, the controller 29 subtracts the reference signal (FIG. 7B) from the scattered detector current versus time information for the defective patterned wafer 65b (FIG. 7C). FIG. 7D shows the detector current signal that remains after subtraction. With reference to FIG. 7D, non-zero differences in detector current appear between times t_A and t_C (the first patterned wafer defect signal 73') and t_D and t_F (the second patterned wafer defect signal 75'), indicating the presence of the first patterned wafer defect 73 and the second patterned wafer defect 75 between wafer locations d_A and d_C and d_D and d_F, respectively.

Thus, by comparing the defect-free reference signal (FIG. 7B) to the current signature of the defective patterned wafer 65b (FIG. 7C), the defects located on or between pattern features are easily detected. Only one defect-free patterned wafer scan need be performed and stored by the controller 29 in order to perform defect detection on all subsequent identically patterned wafers. Accordingly, defect detection may be performed on every production wafer in a production line without the need for more than an initial, one time reference scan.

A significant advantage of the present invention is that the polarization isolation of the reflected light beam from the much smaller scattered light beam allows the scattered light beam S_F is more easily detected without

interference from the reflected light background. This allows for reduced size, cost and complexity of the optical pickup 31.

The optical pickup 31 allows the defect detection apparatus to operate at scan rates significantly higher than the rates at which wafers are typically transported through semiconductor device fabrication systems. Therefore, a wafer can be scanned as it travels at its normal speed through a semiconductor device fabrication system (i.e., in situ) as described below with reference to FIG. 8.

FIG. 8 is a top plan view of an automated tool 77 for fabricating semiconductor devices that employs the inventive defect detection apparatus 30 of FIG. 2. The tool 77 comprises a pair of load locks 79a, 79b, and a first wafer handler chamber 81 containing a first wafer handler 83. The first wafer handler chamber 81 is coupled to the pair of load locks 79a, 79b and to a pair of pass-through chambers 85a, 85b within the tool 77. The tool 77 further comprises a second wafer handler chamber 87, containing a second wafer handler 89, coupled to the pair of pass-through chambers 85a, 85b, and to a plurality of processing chambers 91, 93 coupled to the second wafer handler chamber 87. Most importantly, an array of the inventive defect detection apparatus (indicated as 30a-30d) is fixedly mounted to a top surface (not shown) of the second wafer handler chamber 87 along a path through which the second wafer handler 89 transports production wafers. The entire tool 77 is controlled by a controller 95 (which comprises a microprocessor 97 and a memory 99) having a program therein which controls semiconductor wafer transfer among the load locks 79a, 79b, the pass-through chambers 85a, 85b, and the processing chambers 91, 93, and which controls processing therein. The controller program may or may not comprise software code for interpreting detector current information from the array of defect detection apparatus 30a-30d.

In operation, a wafer carrier containing at least one wafer is loaded into the first load lock 79a, and the first load lock 79a is pumped to the desired vacuum level. The first wafer handler 83 extracts the first wafer, transferring the first wafer to the first pass-through chamber 85a. The second wafer handler 89 transfers the first wafer from the first pass-through chamber 85a to the first processing chamber 91. A process then is performed in the first processing chamber 91 (e.g., a pattern etching to form the pattern features 67a-h of FIG. 6A).

After processing within the first processing chamber 91 is complete, the second wafer handler 89 extracts the first wafer and carries it to the second processing chamber 93 for further processing. As the second wafer handler 89 retracts from the first processing chamber 91 while carrying the first wafer, the first wafer travels beneath the array of defect detection apparatus 30a-d. The transmitted light beam T_F of each defect detection apparatus 30a-d strikes the top surface of the first wafer as the first wafer travels thereunder, and defect detection is performed by each defect detection apparatus 30a-d to monitor the quality of the processed first wafer and to aid in the identification of defect sources, as described previously with reference to FIGS. 2-7D.

In a conventional defect detection apparatus, a wafer must be clamped during defect detection to prevent the wafer from wobbling during the wafer translations required for the detection process. Clamping the wafer generates particles at the clamp/wafer interface that may further contaminate the wafer. Because of the large dynamic focal range of the inventive defect detection apparatus 30, the first wafer need not be clamped during translation. Thus, no particles are generated during defect detection.

The entire surface area of the first wafer is scanned for defects as the first wafer is translated below

the array of defect detection apparatus 30a-d. The array of defect detection apparatus allows a much larger surface area (or the entire surface area) of the first wafer to be inspected for defects during wafer extraction from the first processing chamber 91. Defect detection, as well as wafer detection and wafer center finding, also can be performed as the first wafer is loaded into the first processing chamber 91.

A solid-state non-linear optical deflector such as an acousto-optic deflector also may be employed to redirect the transmitted light beam T_F so as to increase the surface area of the first wafer scanned during wafer transfer (as described below with reference to FIG. 9). That is, the acousto-optic deflector may scan the transmitted light beam T_F in one dimension while the wafer handler scans the transmitted light beam T_F in a second (e.g., orthogonal) direction so as to allow for two-dimensional scanning. Such scanning also can be used for wafer detection and wafer center finding during wafer transit if so desired.

Upon arrival at the second processing chamber 93, the first wafer is loaded into the second processing chamber 93, and the second processing step is performed. After the first wafer is processed within the second processing chamber 93, the second wafer handler 89 transfers the first wafer to the second pass-through chamber 85b, and the first wafer handler 83 transfers the first wafer from the second pass-through chamber 85b to either the first or the second load lock 79a, 79b. During the transfer of the first wafer between the second processing chamber 93 and the second pass-through chamber 85b, the above described defect detection process may be repeated via a second array of the inventive defect detection apparatus (not shown) or via a deflector-based defect detection apparatus as described with reference to FIG. 9, if desired. In this manner, the first wafer is inspected for defects following each processing

step, allowing defect sources to be quickly identified. The processing sequence repeats until each wafer within the wafer carrier has been processed and stored in either the first or the second load lock 79a, 79b.

The present invention thus converts non-value added wafer transfer time into valuable defect detection time, and allows a wafer's contamination level to be monitored after every processing step. Wafer quality is therefore guaranteed and material costs due to defective films or patterns are reduced.

By employing the present invention, defect levels may be monitored after every sputtering deposition. A sputtering target, therefore, may be used until the end of its useful life. Accordingly, by using the present defect detection apparatus, target lifetime variations are irrelevant as the maximum useful life of every target is extracted.

FIG. 9 is a block diagram of a deflector-based defect detection apparatus 101 for scanning the surface of a wafer during defect detection. Unlike the array of defect detection apparatus 30a-d of FIG. 8, the deflector-based defect detection apparatus 101 is located external to the second wafer handler chamber 87 and performs defection detection (and wafer center finding and wafer detection if desired) through a vacuum seal window 103 (shown dashed in FIG. 8) in the second wafer handler chamber 87. It will be understood that the deflector-based defect detection apparatus 101 also may be located within the second wafer handler chamber 87.

With reference to FIG. 9, the deflector-based defect detection apparatus 101 comprises a coherent light source 105 such as a laser for supplying a coherent light beam 105a to beam collimator optics 107. The beam collimator optics 107 collimate the light beam 105a to form a collimated light beam 107a.

The defect detection apparatus 101 further comprises an acousto-optic deflector 109 for scanning the collimated light beam 107a over a pre-selected angular range. A beam sweep signal generator 111 supplies via an RF amplifier 113 the frequency range signal (e.g., 55-105 MHz) necessary to scan the surface of a typical semiconductor wafer. The acousto-optic deflector 109 thereby emits a scanned light beam 109a.

The deflector-based defect detection apparatus 101 further comprises an optical pickup 31′ (e.g., an optical pickup such as the optical pickup 31 of FIG. 2 absent the laser source 33) for receiving the scanned light beam 109a and for polarizing the light beam so as to generate the transmitted light beam T_F (as previously described). Because the focusing optics (not shown) within the optical pickup 31′ are configured to focus the transmitted light beam T_F a short distance from the optical pickup 31′, when the optical pickup 31′ is employed external to the second wafer handler chamber 87 (and thus a larger distance from the wafer being scanned), a relay lens 115 is provided to adjust the focal point of the transmitted light beam T_F so that the transmitted light beam T_F remains focused on a wafer being scanned. A field flattening lens 117 (such as a concave plano lens as shown) also is provided to correct for changes in the beam size or beam shape of the transmitted light beam T_F as the light beam scans the focusing optics of the optical pickup 31′.

The light beam T_F thereafter travels from the field flattening lens 117 through the vacuum seal window 103 to the surface of a wafer 119 on which defect detection is to be performed, and a scattered light beam S_A and a reflected light beam R_A are generated as previously described. The scattered light beam S_A and the reflected light beam R_A travel through the vacuum seal window 103, the field flattening lens 117 and the relay lens 115 to the optical

pickup 31'. The controller 29 thereafter interprets scattered light beam information as previously described to affect defect detection.

The foregoing description discloses only the preferred embodiments of the invention, modifications of the above disclosed apparatus and method which fall within the scope of the invention will be readily apparent to those of ordinary skill in the art. For instance, while the inventive defect detection apparatus preferably is positioned within a semiconductor fabrication system, it may be employed external to a semiconductor fabrication system through a quartz window, for example. Also, a higher power light source 33 may be employed for defect detection on low-reflectivity or highly absorbing films or substrates. If desired, the inventive defect detection apparatus also may be employed for on-the-fly wafer center finding and wafer detection.

As an alternative method of defect detection on a patterned wafer, any changes in the detector current of the monitor photodiode 33' corresponding to the location of a known pattern feature may be ignored. Accordingly, only increases in the detector current of the monitor photodiode 33' at wafer locations known to be free from pattern features are treated as defects.

Accordingly, while the present invention has been disclosed in connection with the preferred embodiments thereof, it should be understood that other embodiments may fall within the spirit and scope of the invention, as defined by the following claims.

THE INVENTION CLAIMED IS:

1. A method of detecting defects on a surface of a semiconductor wafer comprising:

providing an optical pickup for scanning a surface of a thin disc and for outputting a signal having a signal level that varies with the presence and the absence of topographical features on the surface of the thin disc;

providing a semiconductor wafer having a surface to be scanned;

scanning the surface of the semiconductor wafer with the optical pickup; and

determining, based on the signal output by the optical pickup during scanning, whether defects are present on the surface scanned by the optical pickup.

2. The method of claim 1 wherein providing an optical pickup comprises providing a polarization-based optical pickup for scanning a surface of a thin disc and for outputting a signal having a signal level that varies with the presence and the absence of topographical features on the surface of the thin disc based on the polarization of light scattered from the surface.

3. The method of claim 1 wherein scanning the surface of the semiconductor wafer comprises translating the semiconductor wafer past the optical pickup at a known rate so as to generate a current signature for the scan.

4. The method of claim 3 further comprising determining the lateral size of a defect based on the current signature.

5. The method of claim 3 further comprising determining the position of a defect based on the current signature.

6. The method of claim 3 further comprising determining whether a topographical feature is a defect based on the current signature.

7. The method of claim 3 further comprising:

providing an array of optical pickups;

scanning a different portion of the surface of the semiconductor wafer with each optical pickup so as to generate a current signature for each scanned portion of the surface of the semiconductor wafer;

determining, based on the current signature for each scanned portion of the surface of the semiconductor wafer, whether defects are present on each scanned portion of the surface of the semiconductor wafer.

8. The method of claim 1 wherein scanning the surface of the semiconductor wafer comprises:

scanning the surface of the semiconductor wafer in a first direction by translating the semiconductor wafer past the optical pickup at a known rate;

providing a deflector apparatus for scanning a light beam transmitted from a light source of the optical pickup; and

scanning the surface of the semiconductor wafer in a second direction with the deflector apparatus.

9. The method of claim 8 wherein providing a deflector apparatus comprises providing an acousto-optic deflector.

10. A method of detecting defects on the surface of a patterned semiconductor wafer comprising:

providing a defect-free patterned wafer having a first pattern;

obtaining a current signature for the defect-free patterned wafer by performing the method of claim 3 on the defect-free patterned wafer;

providing a patterned production wafer having the first pattern;

obtaining a current signature for the patterned production wafer by performing the method of claim 3 on the patterned production wafer;

comparing the current signature of the patterned production wafer to the current signature of the defect-free patterned wafer; and

identifying differences between the current signature of the patterned production wafer and the current signature of the defect-free patterned wafer as defects.

11. The method of claim 10 further comprising distinguishing between a pattern defect and a particle defect based on the defect's shape as provided by the patterned production wafer's current signature.

12. The method of claim 10 further comprising distinguishing between a pattern defect and a particle defect based on the defect's location as provided by the patterned production wafer's current signature.

13. The method defined in claim 10 wherein obtaining the current signature for the production wafer comprises unloading the semiconductor wafer from a processing chamber.

14. A method of detecting defects on the surface of a semiconductor wafer comprising:

providing a defect-free wafer;

obtaining a reference current signature for the defect-free wafer by performing the method of claim 3 on the defect-free wafer;

providing a production wafer, which aside from any defects on the production wafer, is identical to the defect-free wafer;

obtaining a current signature for the production wafer by performing the method of claim 3 on the production wafer;

comparing the current signature of the production wafer to the reference current signature; and

identifying differences between the current signature of the production wafer and the reference current signature as defects.

15. The method defined in claim 14 wherein obtaining the current signature for the production wafer comprises unloading the semiconductor wafer from a processing chamber.

16. A method of optimizing a sputtering target's useful life comprising:

providing a semiconductor wafer having a surface;

providing a sputtering target;

sputtering the sputtering target to form a film of target material on the surface of the semiconductor wafer;

performing the method of claim 1 on the surface of the semiconductor wafer to detect defects in the film of target material; and

discarding the sputtering target if the number of detected defects exceeds a predetermined threshold.

17. An apparatus for detecting defects on a surface of a semiconductor wafer comprising:

an optical pickup for scanning a surface of a thin disc and for outputting a signal having a signal level that varies with the presence and the absence of topographical features on the surface of the thin disc; and

a controller coupled to the optical pickup programmed for determining the presence and the absence of defects on a surface of a semiconductor wafer based on the signal output by the optical pickup as the surface of the semiconductor wafer is scanned by the optical pickup.

18. The apparatus of claim 17 wherein the optical pickup comprises a polarization-based optical pickup for scanning a surface of a thin disc and for outputting a signal having a signal level that varies with the presence and the absence of topographical features on the surface of the thin disc based on the polarization of light scattered from the surface.

19. The apparatus of claim 17 wherein the controller comprises a memory for storing a reference signal output from the optical pickup during the scan of a defect-free semiconductor wafer, the controller further programmed for comparing the reference signal to subsequent signals output from the optical pickup during the scan of subsequent semiconductor wafers so as to affect defect detection.

20. The apparatus of claim 17 further comprising a deflector for scanning the surface of the semiconductor wafer with a light beam transmitted from the optical pickup.

21. The apparatus of claim 17 further comprising an array of optical pickups, each optical pickup coupled to the controller.

22. A semiconductor device fabrication system comprising:

a transfer chamber comprising a transfer mechanism;

the apparatus of claim 17 coupled to the transfer chamber for detecting defects on a surface of a semiconductor wafer being transferred by the transfer mechanism; and

a first chamber coupled to the transfer chamber for processing the semiconductor wafer.

23. The apparatus of claim 22 further comprising a plurality of optical pickups coupled to the transfer chamber.

24. The apparatus of claim 22 wherein the optical pickup is coupled to a vacuum seal window of the transfer chamber ex-situ.

25. The apparatus of claim 22 further comprising a deflector coupled to the optical pickup for scanning a light beam transmitted from the optical pickup across the surface of the semiconductor wafer.

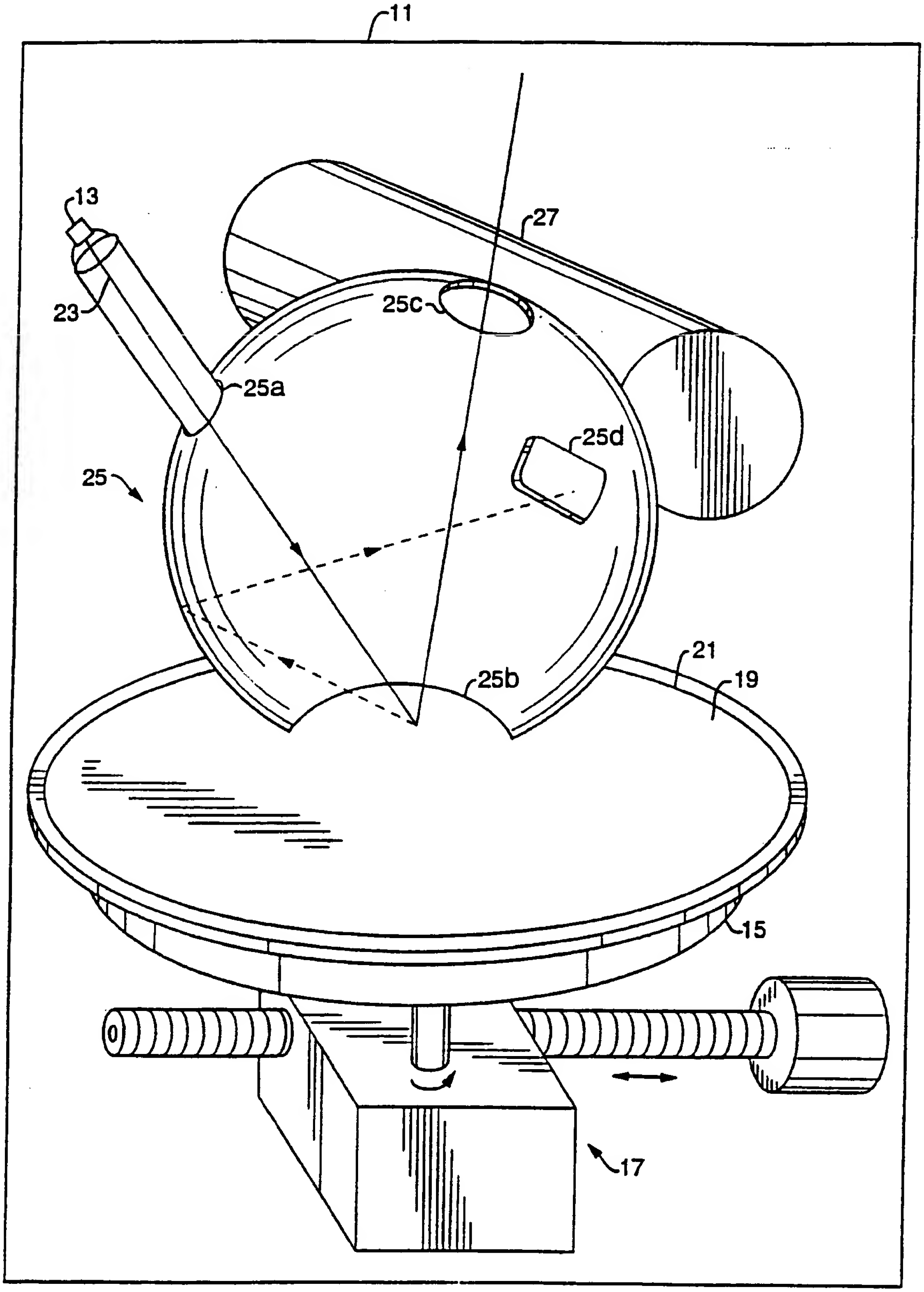


FIG. 1A
(PRIOR ART)

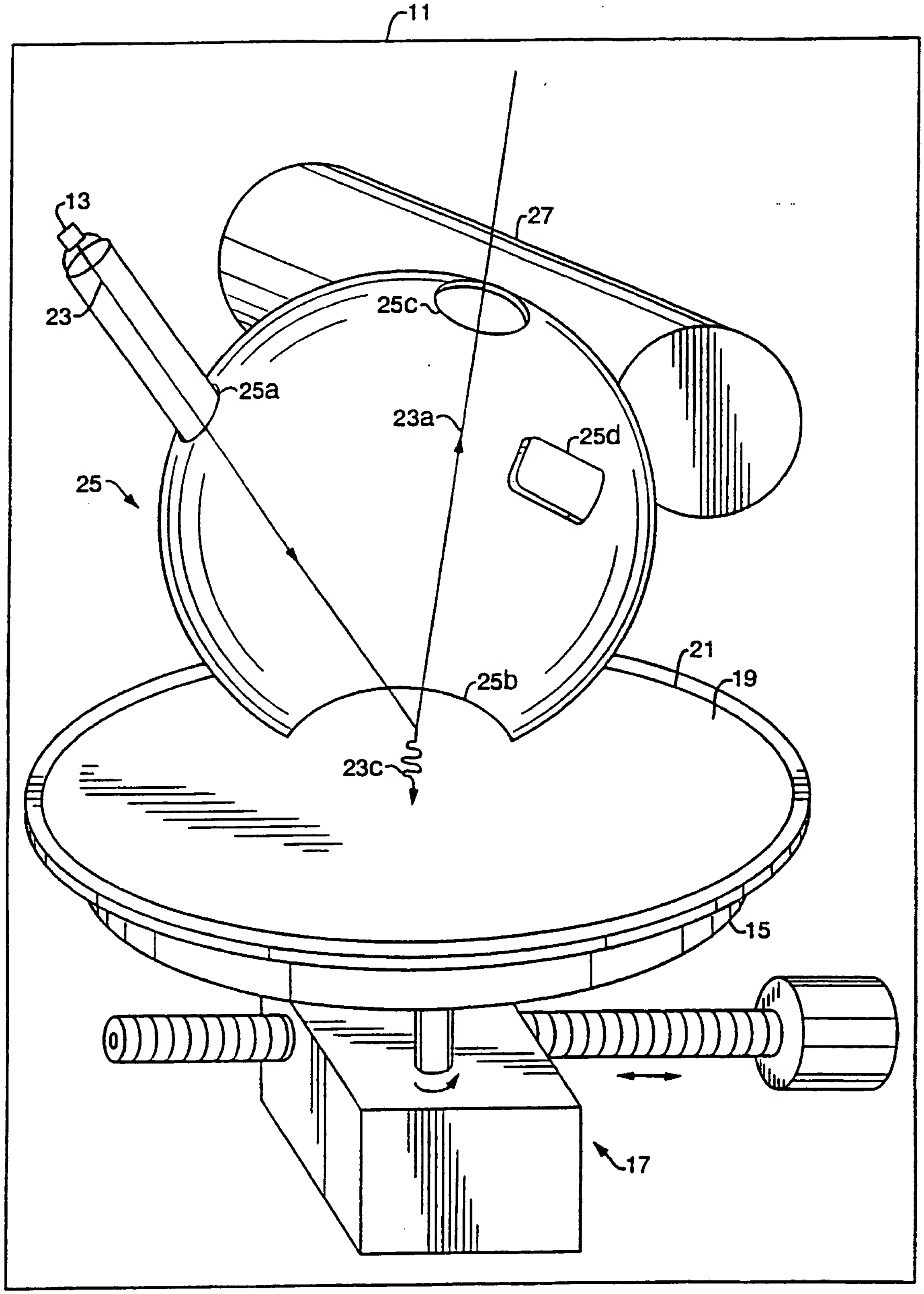


FIG. 1B
(PRIOR ART)

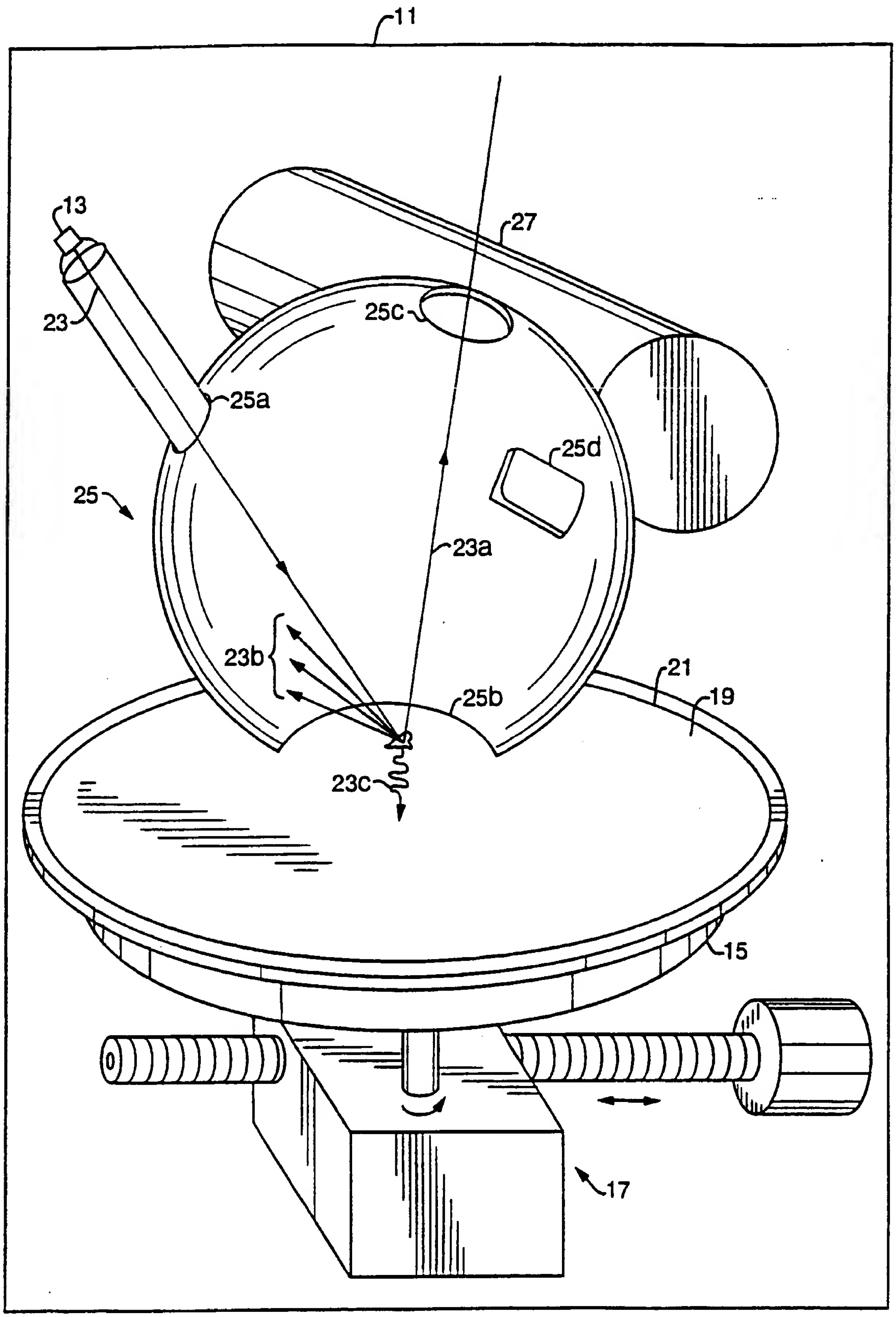


FIG. 1C
(PRIOR ART)

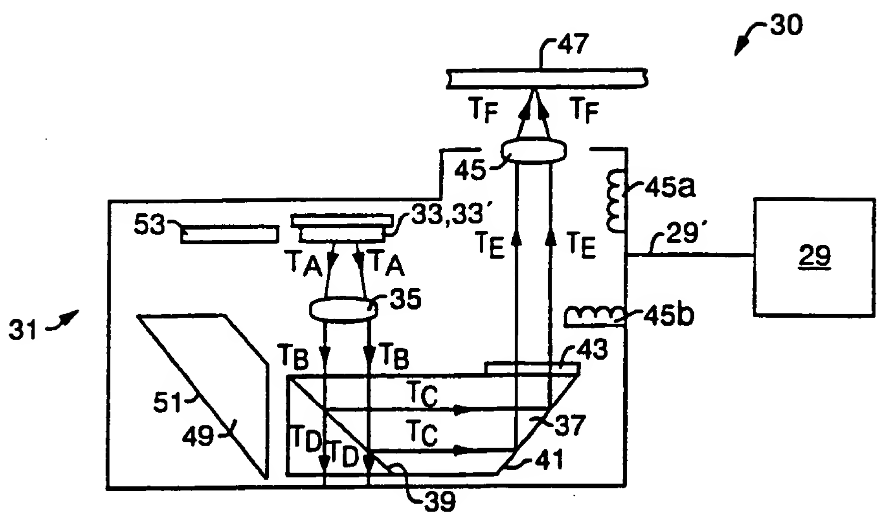
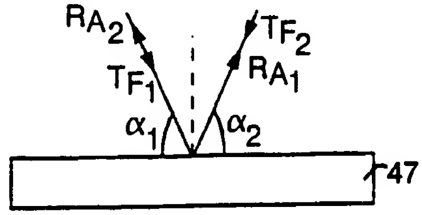

30
47
T_F
T_F
45
45a
53
33,33'
T_E
T_E
29'
29
T_A
T_A
35
31
45b
T_B
T_B
43
51
T_C
37
49
T_D
T_C
T_D
41
39

FIG. 2



$\alpha_1 = \alpha_2$

FIG. 3A

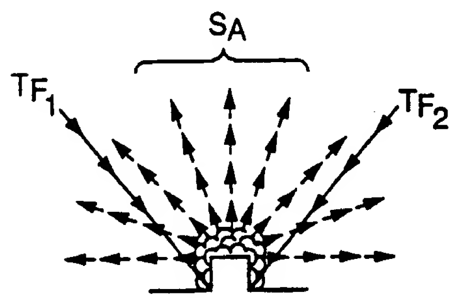


FIG. 3B

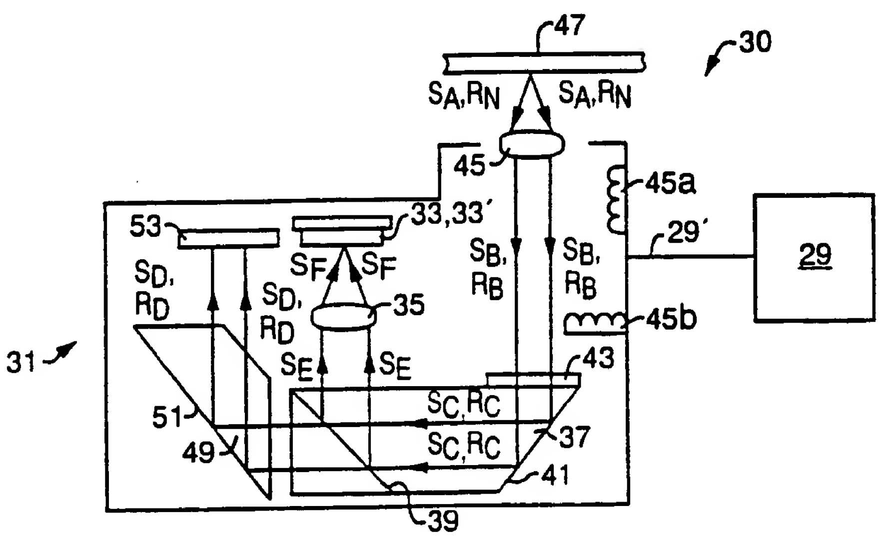


FIG. 3C

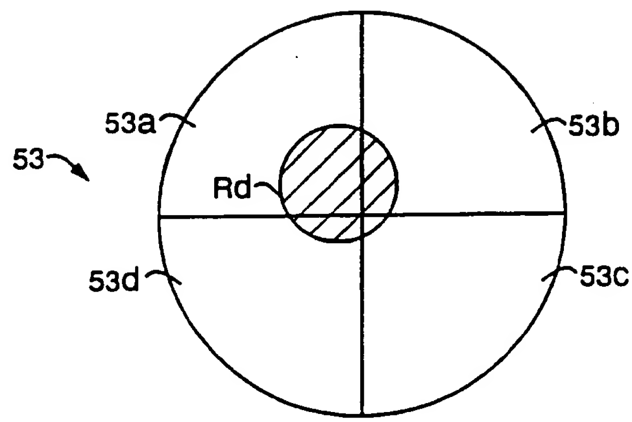


FIG. 4A

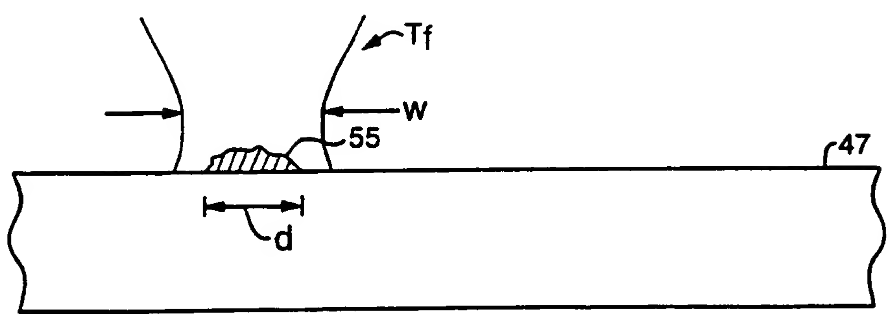


FIG. 4B

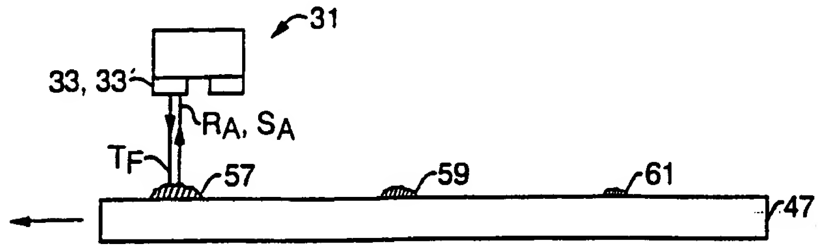


FIG. 5A

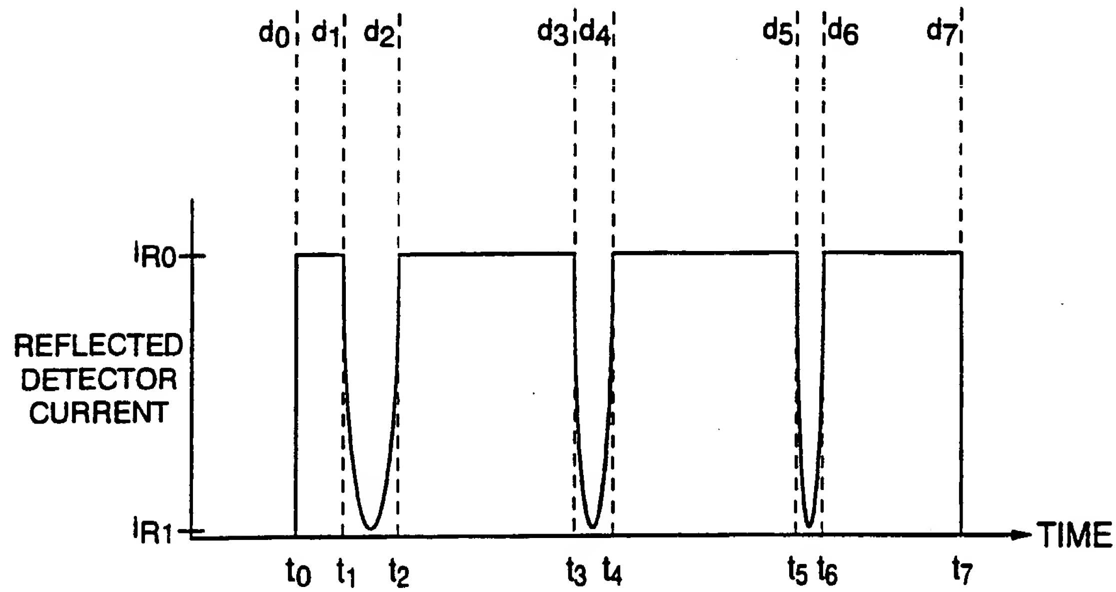


FIG. 5B

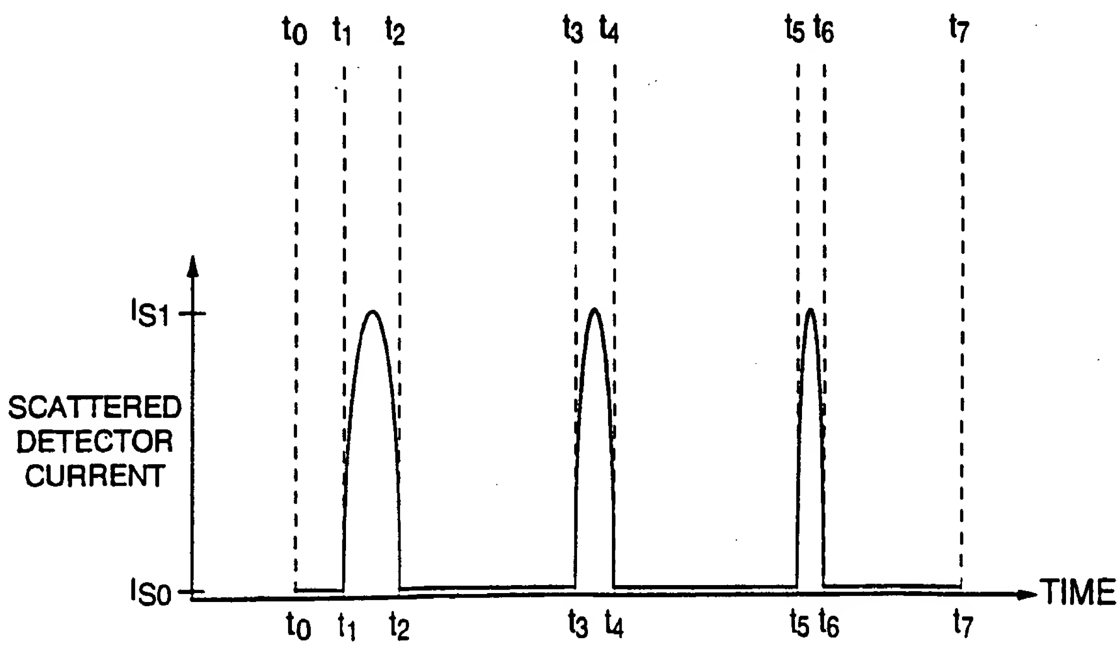


FIG. 5C

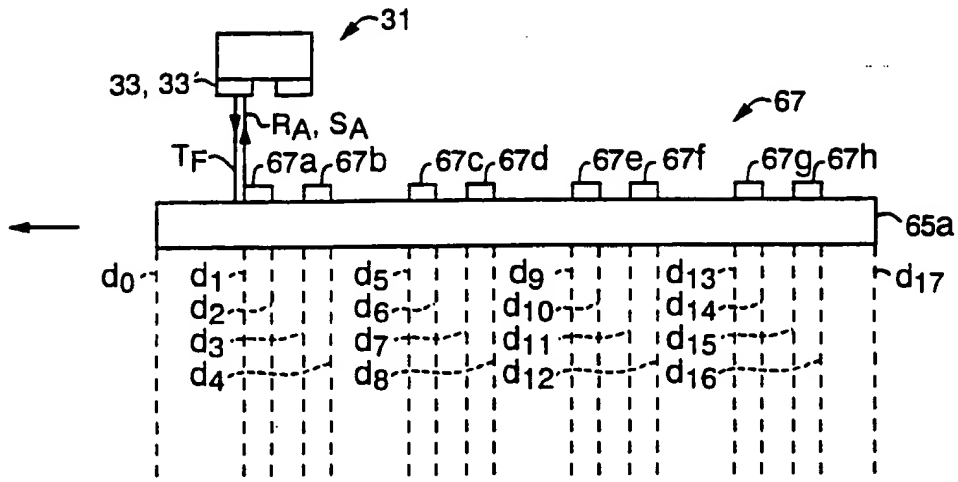

31
33, 33'
R_A, S_A
T_F
67
67a 67b 67c 67d 67e 67f 67g 67h
65a
d_0 d_1 d_2 d_3 d_4 d_5 d_6 d_7 d_8 d_9 d_{10} d_{11} d_{12} d_{13} d_{14} d_{15} d_{16} d_{17}

FIG. 6A

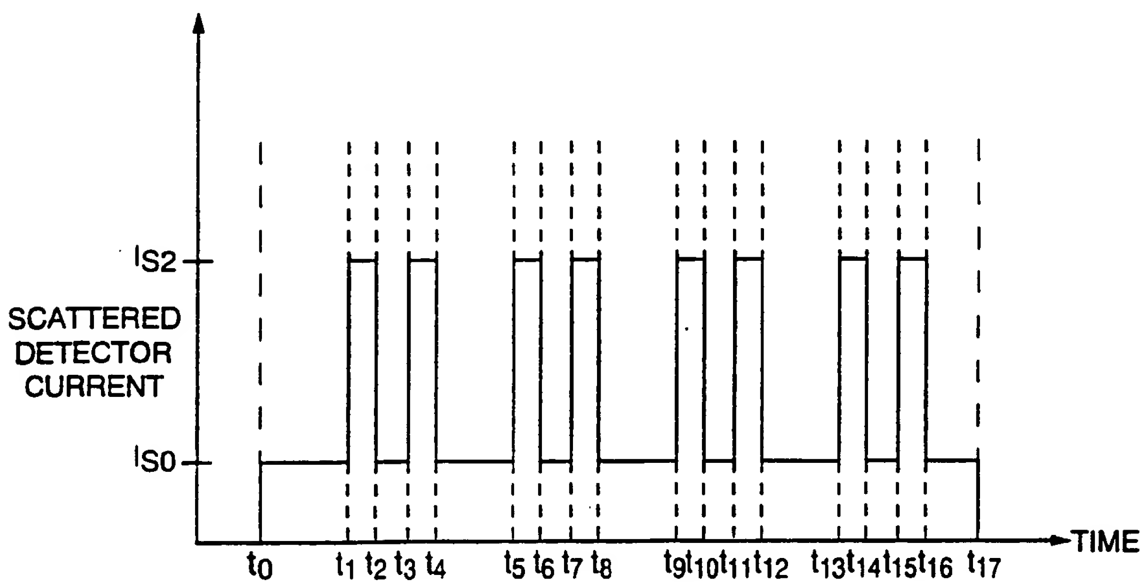

I_{S2}
SCATTERED DETECTOR CURRENT
I_{S0}
TIME
t_0 t_1 t_2 t_3 t_4 t_5 t_6 t_7 t_8 t_9 t_{10} t_{11} t_{12} t_{13} t_{14} t_{15} t_{16} t_{17}

FIG. 6B

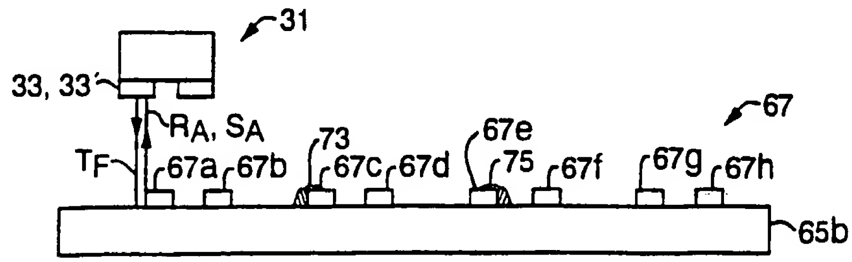


FIG. 7A

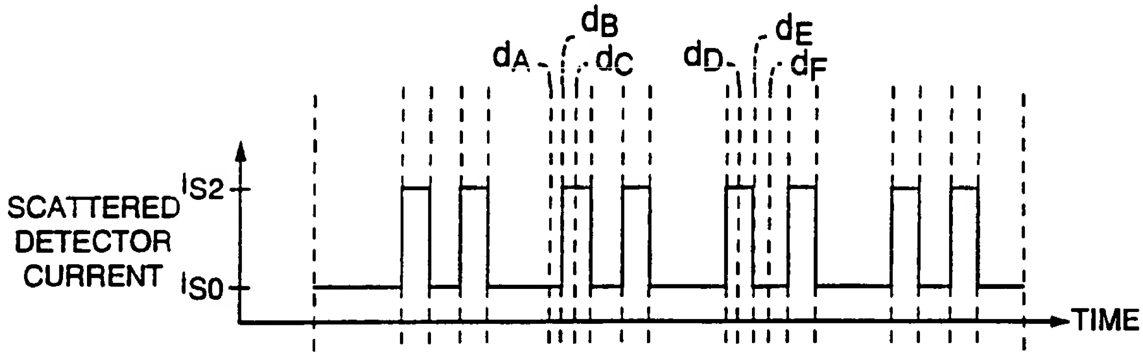


FIG. 7B

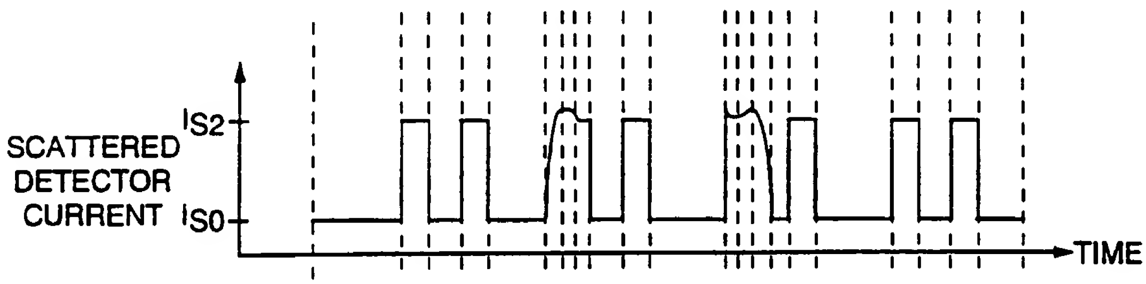


FIG. 7C

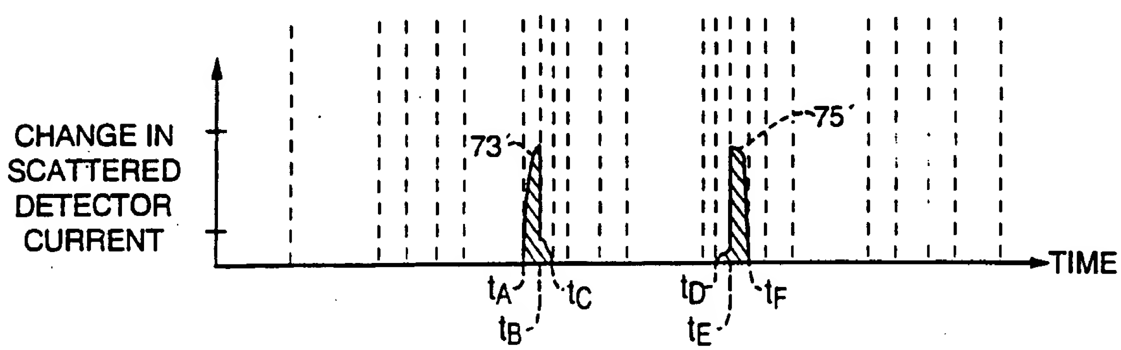


FIG. 7D

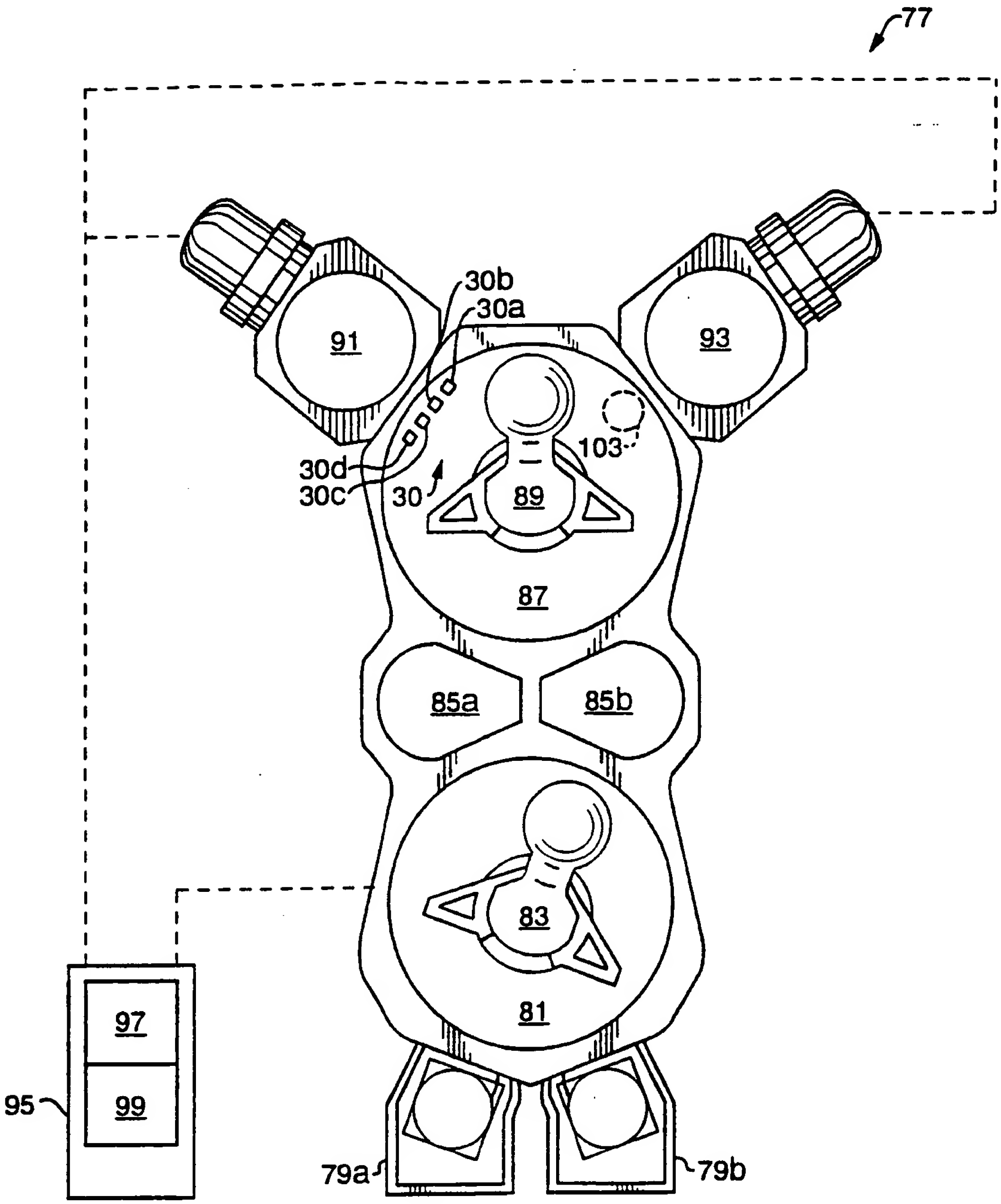


FIG. 8

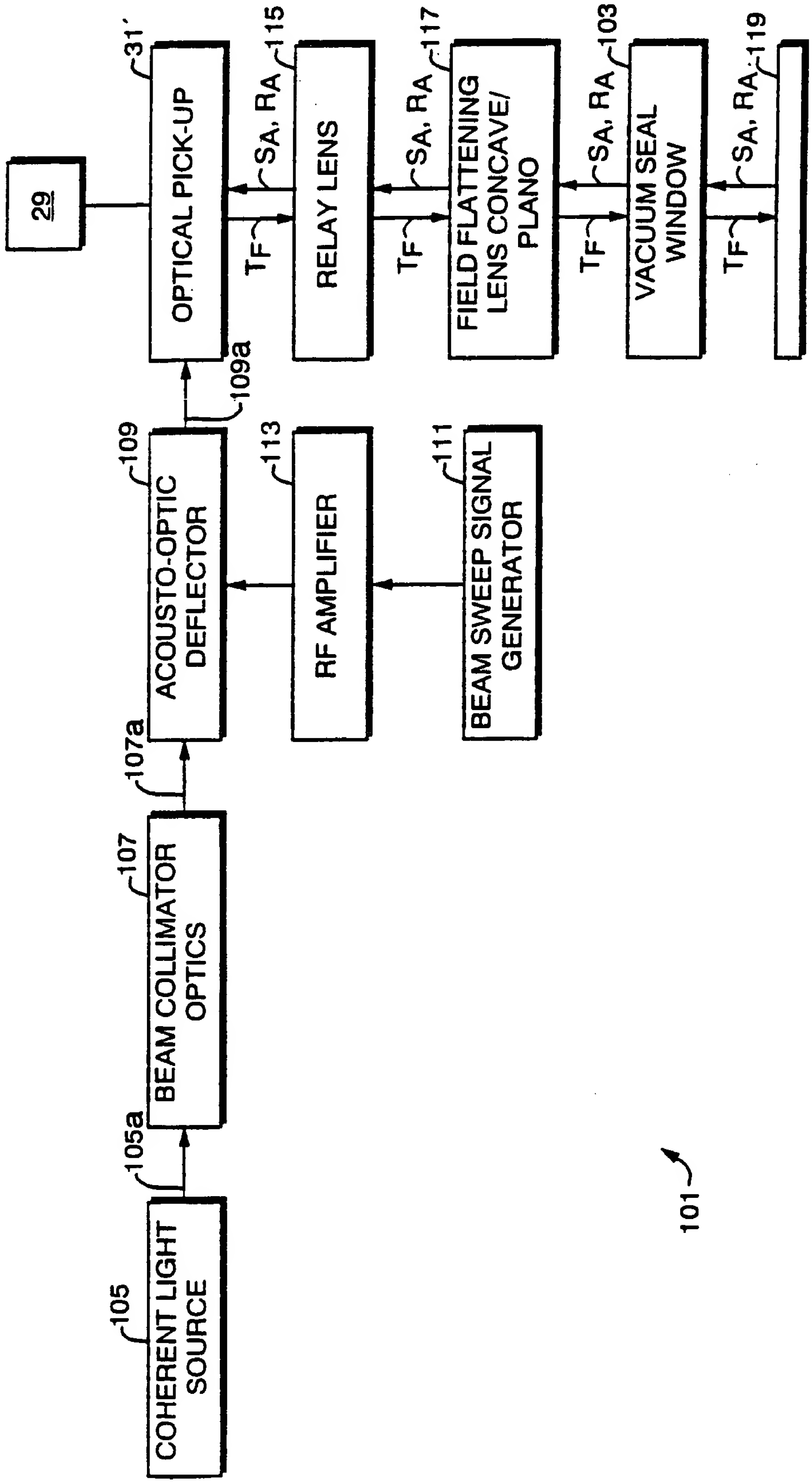

29
OPTICAL PICK-UP
31'
RELAY LENS
115
FIELD FLATTENING LENS CONCAVE/ PLANO
117
VACUUM SEAL WINDOW
103
119
TF
SA, RA
109a
ACOUSTO-OPTIC DEFLECTOR
109
RF AMPLIFIER
113
BEAM SWEEP SIGNAL GENERATOR
111
107a
BEAM COLLIMATOR OPTICS
107
105a
COHERENT LIGHT SOURCE
105
101

FIG. 9

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/25549

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01N21/88 H01L21/66

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01N H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 97 46865 A (TENCOR INSTRUMENTS) 11 December 1997 (1997-12-11)	1-6,8,9, 17,18, 20,21
Y	abstract page 5, line 25 - line 34 page 9, line 33 - line 35 page 10, line 16 - line 19 page 13, line 5 -page 15, line 3 page 15, line 10 - line 1 page 17, line 3 - line 31 figures 3,6,10 --- -/--	7,10,14, 19,21,22

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
6 March 2000	14/03/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Verdoodt, E

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5 774 222 A (NAKAYAMA YASUHIKO ET AL) 30 June 1998 (1998-06-30)	10,14,19
Y	abstract	10,14,19
A	column 2, line 55 - line 59 column 7, line 27 - line 46 column 30, line 51 -column 31, line 14 column 36, line 32 - line 44	11,12,16
Y	US 5 463 459 A (MATSUOKA KAZUHIKO ET AL) 31 October 1995 (1995-10-31) column 14, line 20 - line 66 figures 15,16	7,21
Y	WO 98 44330 A (MICROTHERM LLC) 8 October 1998 (1998-10-08)	22
A	figures 6,9	24
A	US 5 355 212 A (WELLS KEITH B ET AL) 11 October 1994 (1994-10-11) abstract column 3, line 8 - line 25 column 4, line 4 - line 9	1,10,17

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 99/25549

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
WO 9746865	A	11-12-1997	AU	3376597 A	05-01-1998
			EP	0979398 A	16-02-2000
US 5774222	A	30-06-1998	JP	8162511 A	21-06-1996
US 5463459	A	31-10-1995	JP	5218163 A	27-08-1993
			US	5274434 A	28-12-1993
			KR	9705689 B	18-04-1993
WO 9844330	A	08-10-1998	AU	6942998 A	22-10-1998
			US	5909276 A	01-06-1999
US 5355212	A	11-10-1994	WO	9503540 A	02-02-1995